Packed Bed Reactor Experiment: Operating a Two-Phase Reactor Bed in Space

In Honor of Vemuri Balakotaiah's Birthday

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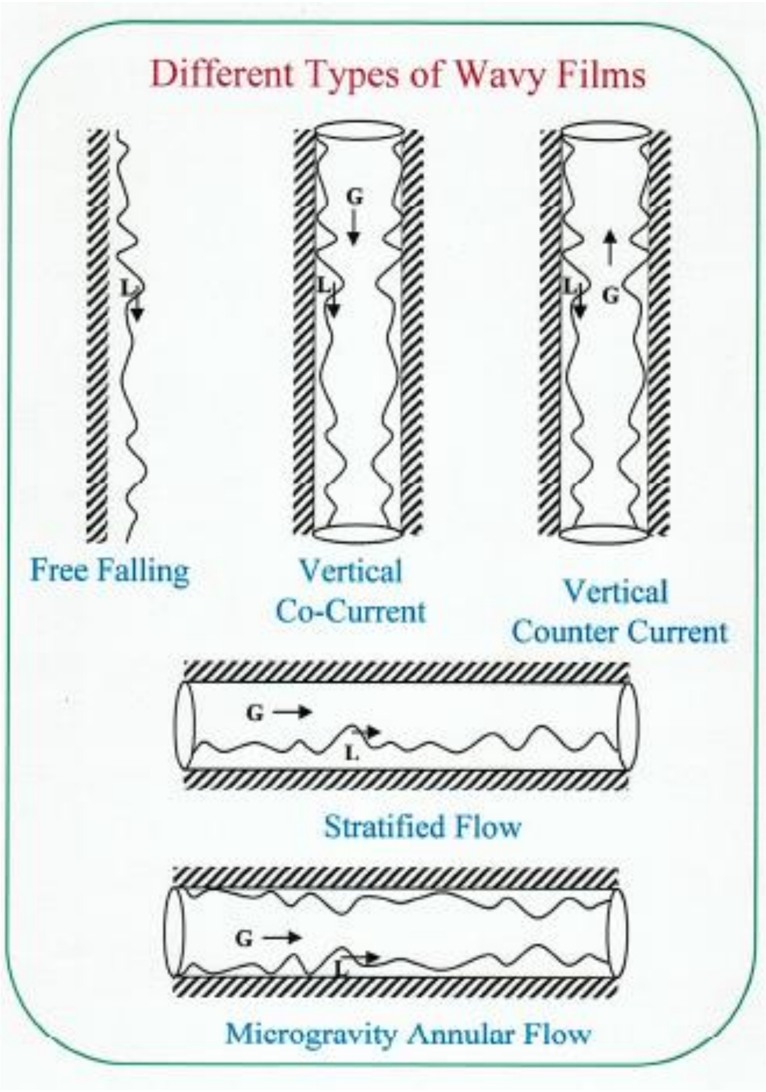
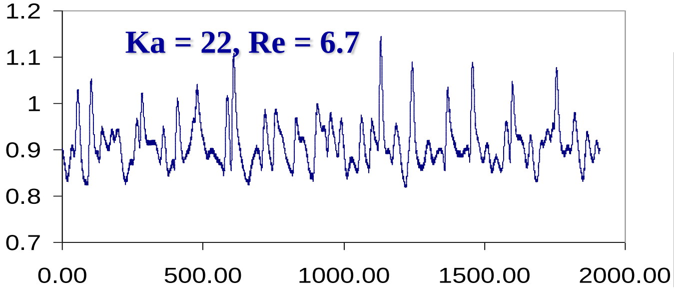
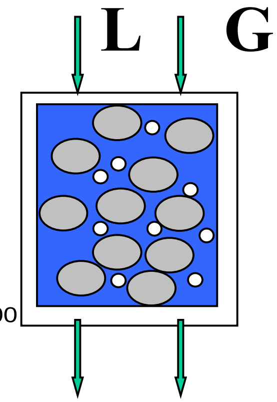
Multiphase Flow



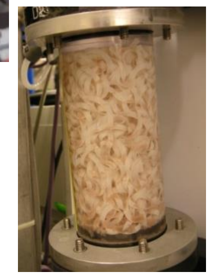
- Gas-liquid flow through pipes in normal and microgravity
  - Experimental and modeling studies on wavy films
- G-L flow through packed-beds in microgravity
  - Gravity effects on multiphase flow



Wave profile on a vertically falling film



Objective and Motivation in (PBRE)



Objective

Study hydrodynamics of packed beds in microgravity and under different flow regimes

Motivation

Current/Future Space Applications:

- Advanced Water Recovery System (AWRS)
- Volatile Removal Assembly (VRA)
- IntraVenous Water GENeration (IVGEN)
- Microbial Check Valve (MCV)
- Activated Carbon/Ion Exchange (ACTEX)
- Ion Exchange for Calcium Removal (in development)

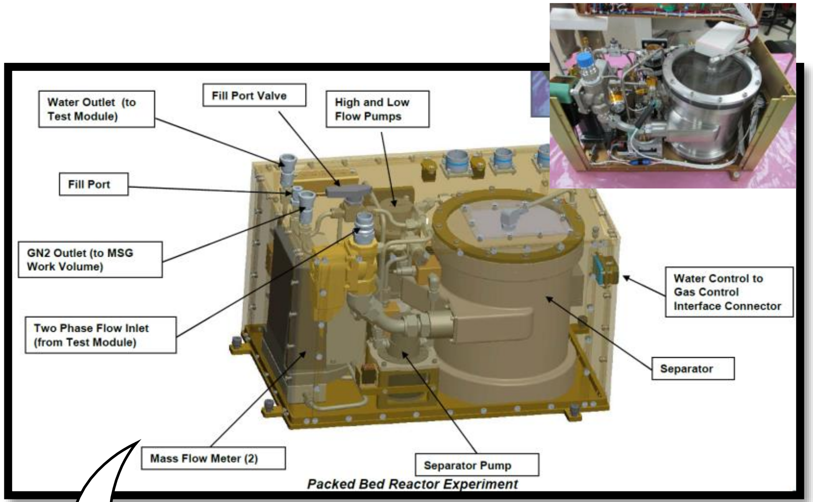
Aircraft, PBRE, PBRE-2

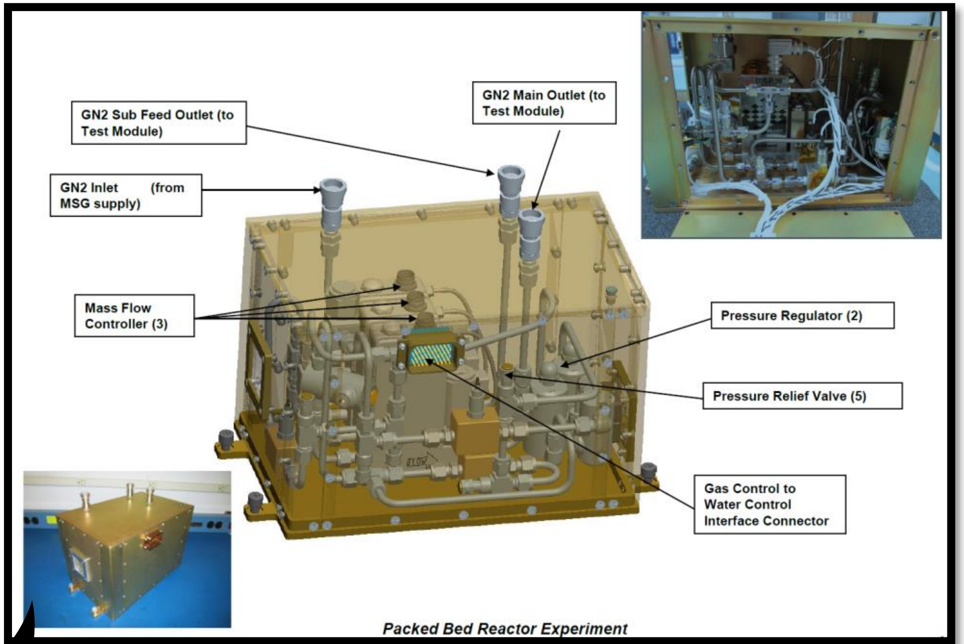
- NASA identified the need to conduct **aircraft flights** to develop an empirical prediction for pressure drop in two-phase flows through porous media for water reclamation processes.

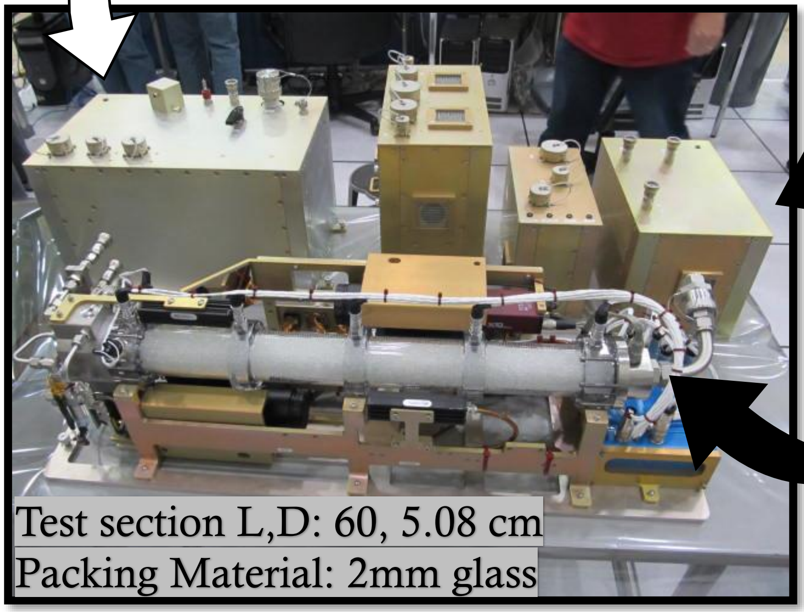
    - ✓ Limitation: Short time interval of low gravity (20 s)
    - ✓ Development of the **ISS PBRE** experiment to deliver a wide range of gas and liquid flows
    - ✓ Reducing the particle size in **PBRE-2** from 3 mm to 2 mm
    - ✓ Modifying the inlet mixing head to minimize the external disturbances

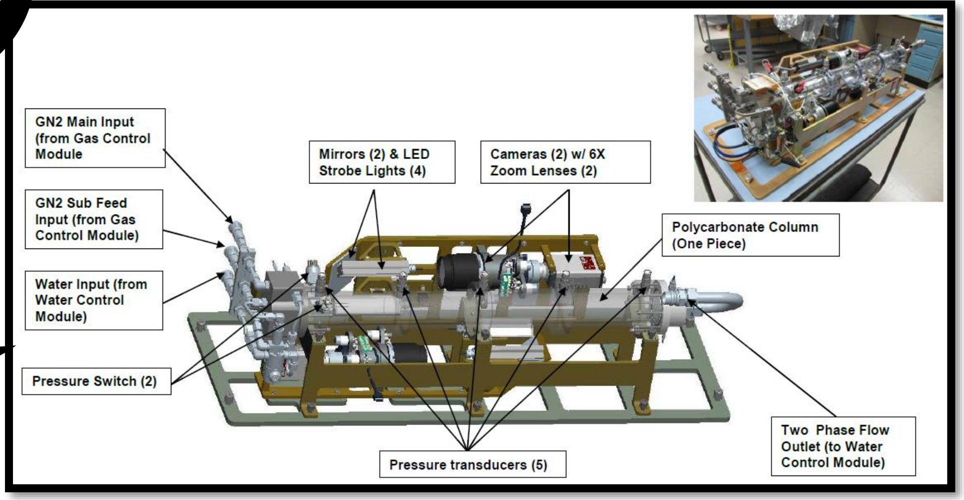
- Goal: Analyzing the experimental data and developing a method to estimate pressure drop through porous media in the microgravity environment.

PBRE Modules









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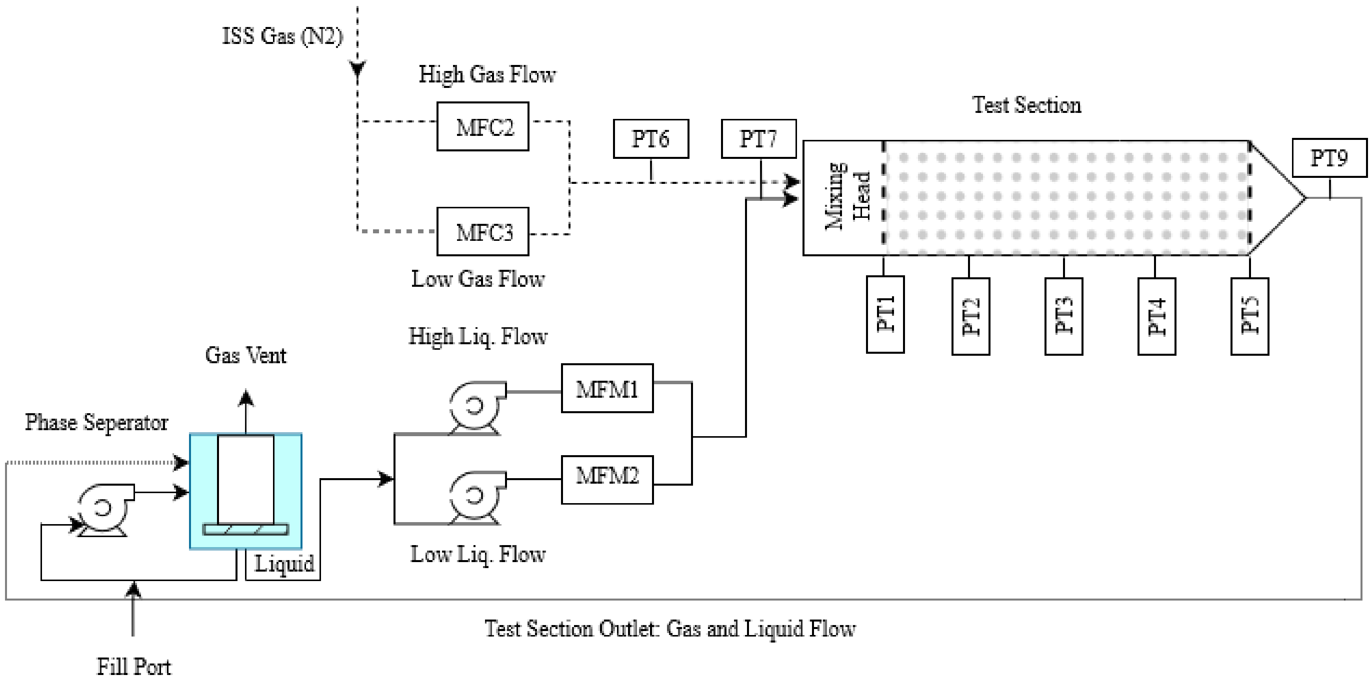
PBRE Flow Loop



Fluid	Range
Nitrogen Gas (kg/hr)	$0.001 < G < 1$ $0.02 < Re^*_{GS} < 23$
Water (kg/hr)	$1 < L < 150$ $0.5 < Re^*_{LS} < 72$

Testing Sequence

Start-up:

- Initial condition of the bed is dry.
- Liquid flush and Gas flush between each test.

✓ Over 200 test points were recorded.

Steady Flow:

- Liquid flush and Gas flush

  After flushing the column for 30 s, the desired gas and liquid flow rates were flown for a duration long enough to establish pseudo-steady flow

Transient Flow:

- To check for the presence of hysteresis in the pressure drop versus flow rates.

Single-Phase Pressure Drop in Porous Media

- Viscous limit: Re_p<10, (ΔP proportional to U) $$f = \frac{150}{Re_p}$$ Blake-Kozeny (1922 – 27)

- Inertial limit: Re_p>1000, (ΔP proportional to U^2) $$f = 1.75$$ Burke-Plummer (1928)

➢ Single Phase Ergun Eq.

$$f = \frac{(-\Delta P)}{\rho U_D^2} \frac{d_p}{L} \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{150}{Re_p} + 1.75$$

Ergun (1952)

or $$\frac{(-\Delta P)}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U_D}{d_p^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho U_D^2}{d_p}$$

$$\boxed{f = \frac{C_V}{Re_p} + C_I}$$

Two-Phase Pressure Drop in 0-g
Modified Ergun Eq.

$$Su_L = \frac{Re_{LS}^2}{We_{LS}} = \frac{d_p \rho_L \sigma}{\mu_L^2} \quad \textit{Suratman number}$$

$$Re_{LS}^* = Re_{LS} / (1-\varepsilon) \quad \textit{Modified Reynols number}$$

$$Ca_{LS}^* = \frac{\mu_L U_{LS}}{\sigma(1-\varepsilon)} \quad \textit{Modified Capillary number}$$

$$f_{TP} = \frac{C_V}{Re_{LS}^*} + C_I + \underbrace{C_S (Re_{GS}^*)^{\alpha} (Re_{LS}^*)^{\beta} (Su_L)^{\gamma}}_{\text{Dynamic phase interaction term}}$$

$$f_{TP} \equiv \frac{-\Delta P}{Z} \frac{d_p}{\rho_L U_{LS}^2} \frac{\varepsilon^3}{1-\varepsilon} = f_{SP} + C_S (Re_{GS}^*)^{\alpha} (Ca_{LS}^*)^{\beta} (Su_L)^{\beta+\gamma}$$

α,β, γ determined by regression

$$f_{TP} = \frac{C_V + C_S \left(Re_{GS}^*\right)^{\alpha} (Re_{LS}^*)^{\beta+1} Su_L^{\gamma}}{Re_{LS}^*} + C_I$$

C_V = 150.8, **C_I** = 1.78, and **ε**=0.358
(for PBRE-2 single-phase data)

$$\frac{-\Delta P}{Z} = \underbrace{C_V \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_l U_{LS}}{d_p^2}}_{\textbf{Viscous}} + \underbrace{C_I \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho_l U_{LS}^2}{d_p}}_{\textbf{Inertial}} + \underbrace{C_S \frac{(1-\varepsilon)}{\varepsilon^3} \left(\frac{\rho_l U_{LS}^2}{d_p}\right) \left(\frac{\rho_g U_{GS} d_p}{\mu_g (1-\varepsilon)}\right)^{\alpha} \left(\frac{\rho_l U_{LS} d_p}{\mu_l (1-\varepsilon)}\right)^{\beta} \left(\frac{d_p \rho_l \sigma}{\mu_l^2}\right)^{\gamma}}_{\textbf{Capillary}}$$

Friction Factor Correlations and Pressure Gradient Plots

- **Dispersed Bubble Regime (DB):**

$$f_{TP} - f_{SP} = 0.07\,(Re^{*}_{GS})^{0.26}(Re^{*}_{LS})^{-0.5}Su_L^{2/3}$$

- **Pulse Regime (P):**

$$f_{TP} - f_{SP} = 0.12\,(Re^{*}_{GS})^{0.35}(Re^{*}_{LS})^{-0.82}Su_L^{2/3}$$

- **Elongated Bubble Regime (EB):**

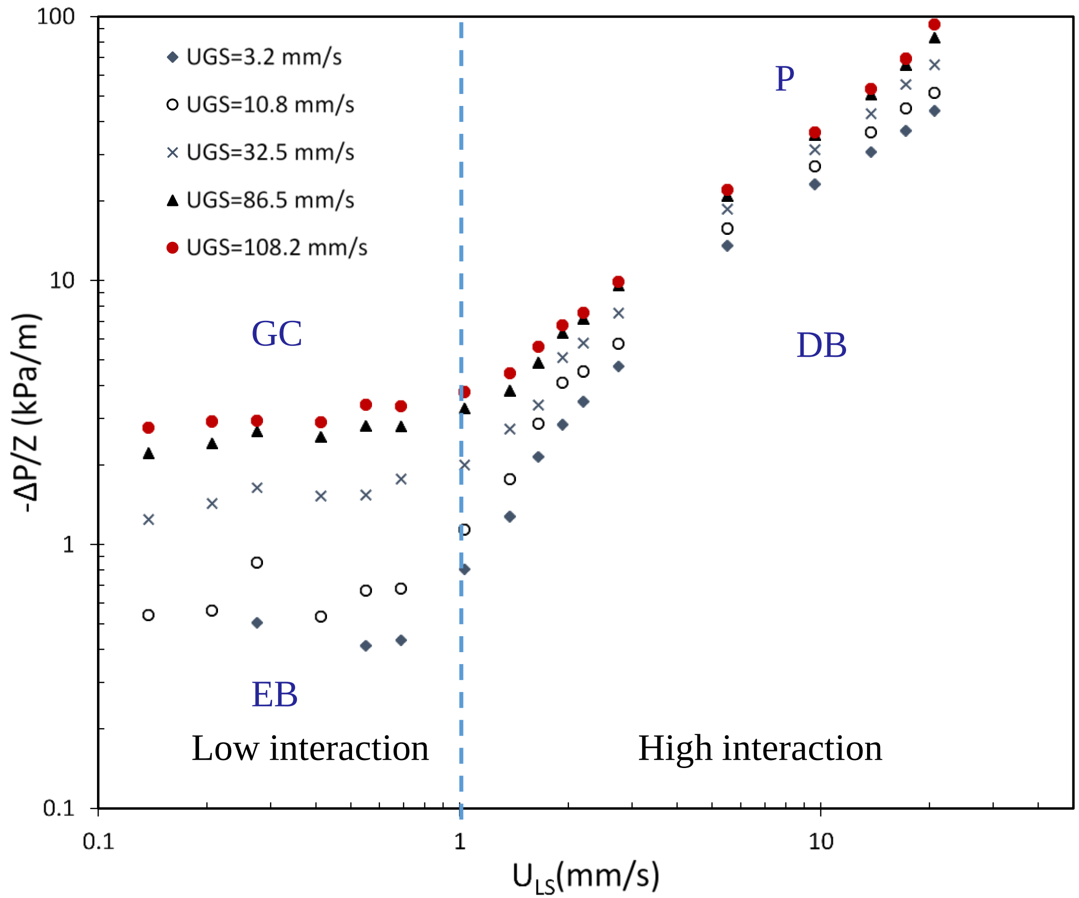
$$f_{TP} - f_{SP} = 0.26\,(Re^{*}_{GS})^{0.24}(Re^{*}_{LS})^{-1.83}Su_L^{2/3}$$

- **Gas Channeling Regime (GC):**

$$f_{TP} - f_{SP} = 0.21\,(Re^{*}_{GS})^{0.66}(Re^{*}_{LS})^{-1.86}Su_L^{2/3}$$

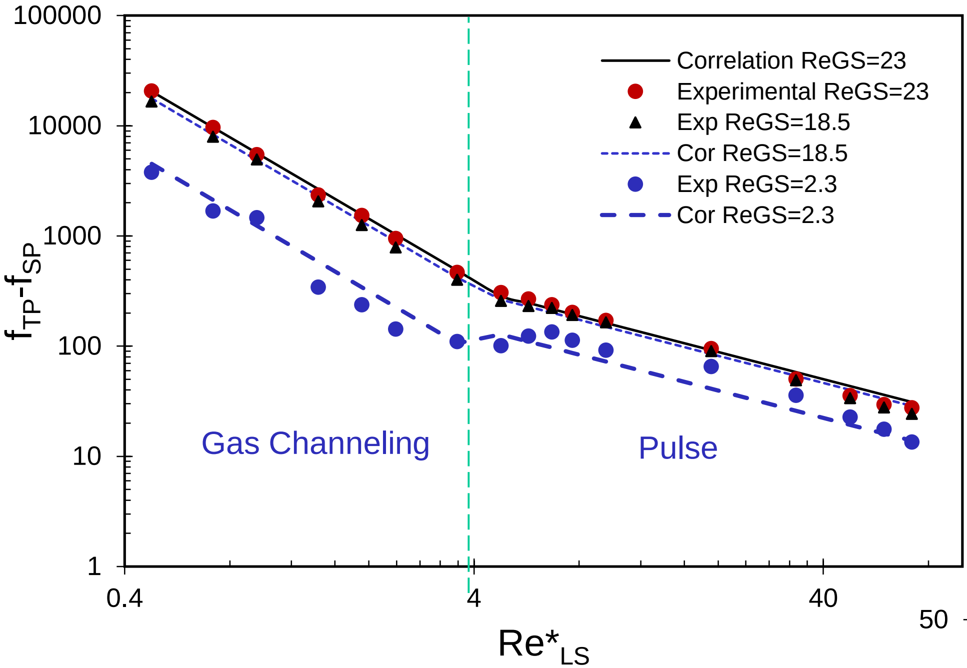
✓ Slope change at $U_{LS} \approx 1$mm/s

✓ Separates the low-interaction region from the high-interaction

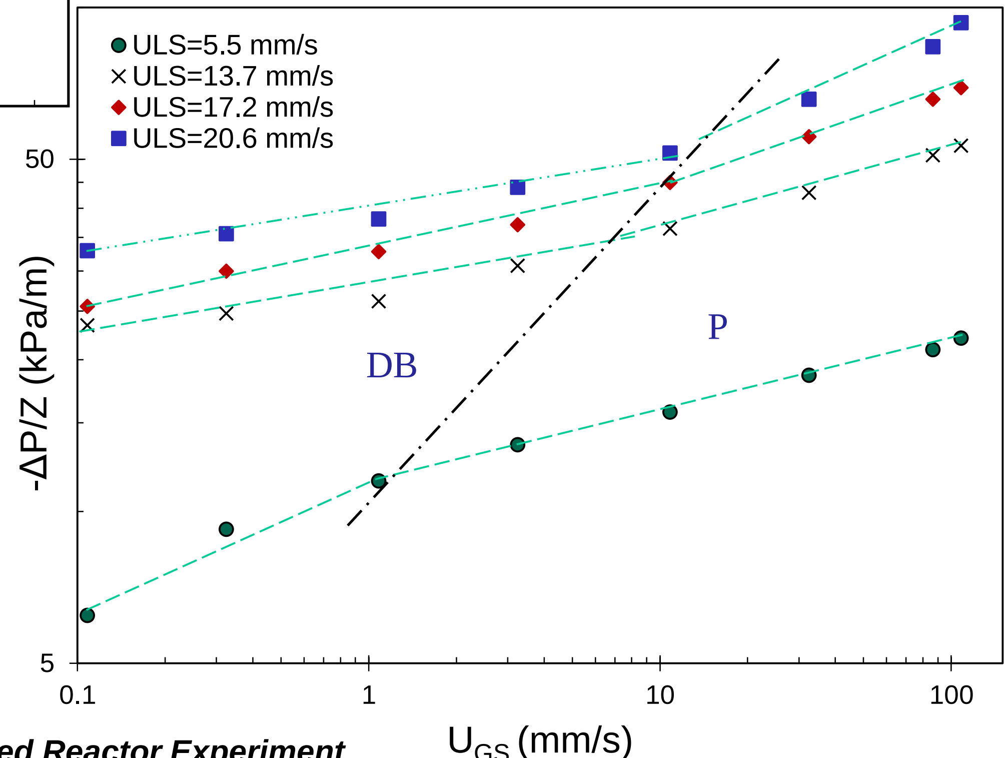


Packed Bed Reactor Experiment

Friction Factor and Pressure Gradient Plots



- ✓ Two different slopes are observed.
- ✓ The slope change occurs at the flow regime transition boundaries.



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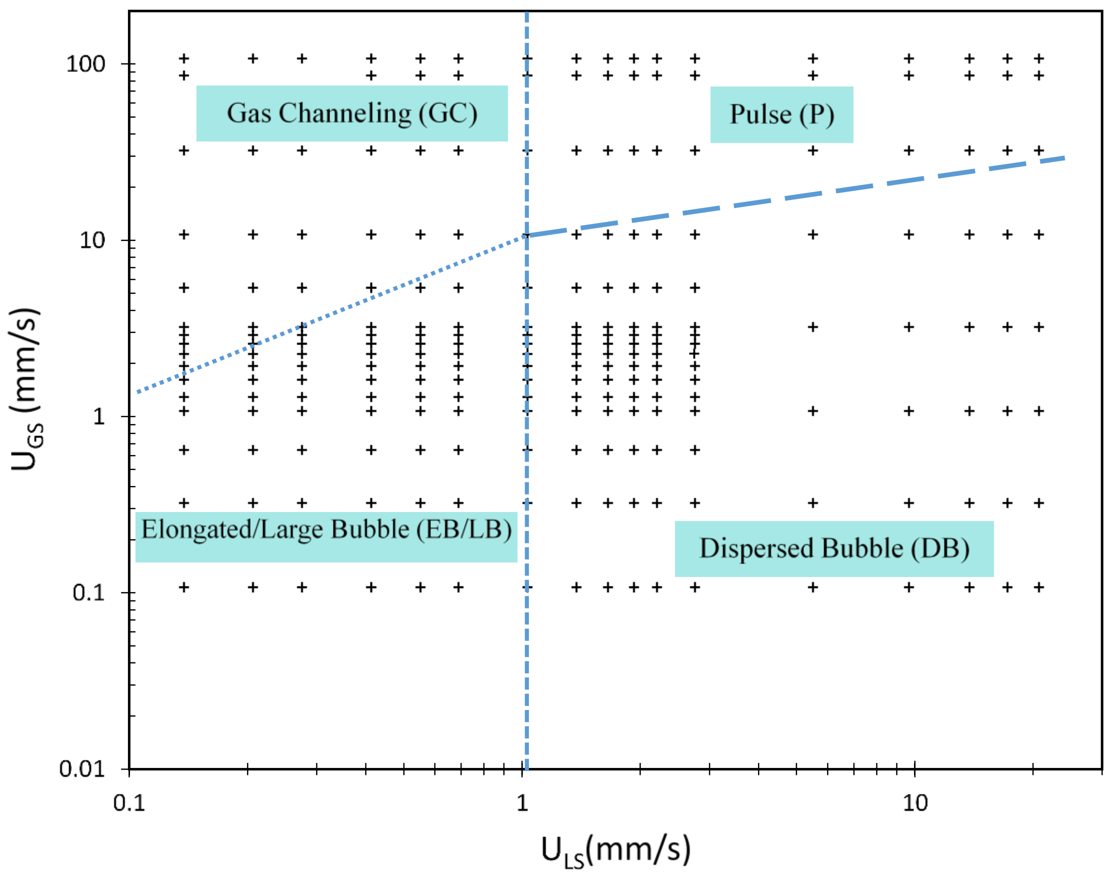
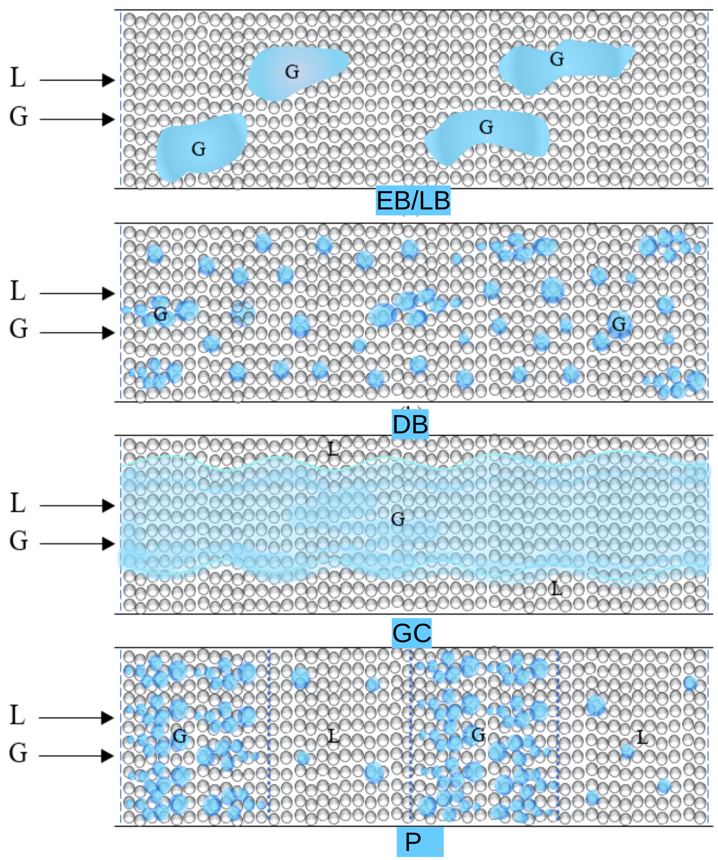
Flow Regimes in Microgravity





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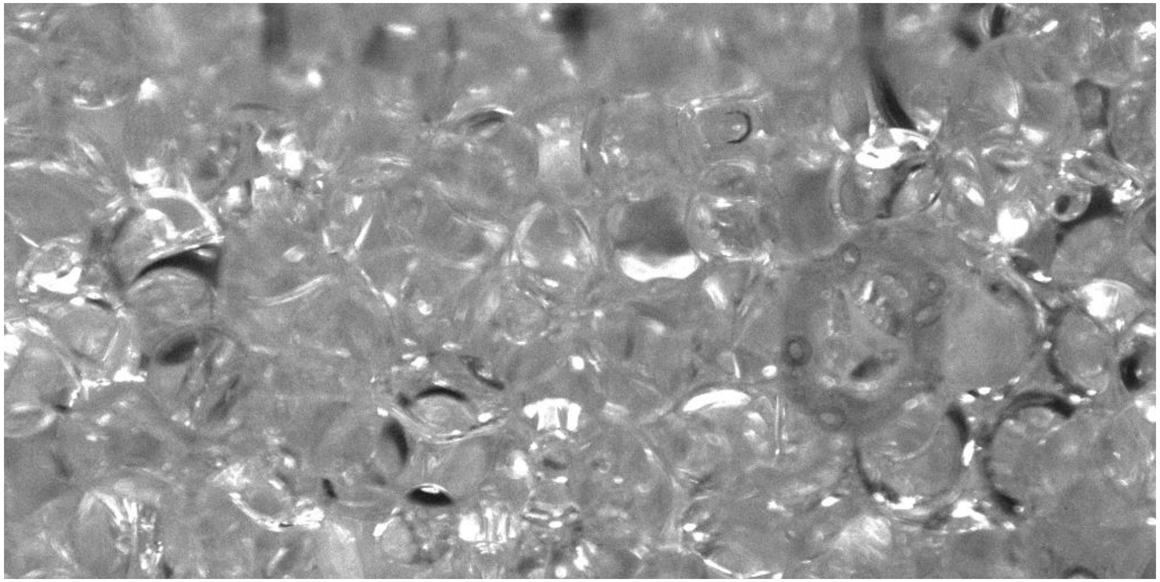
Examples of Large Bubbles in the Bed

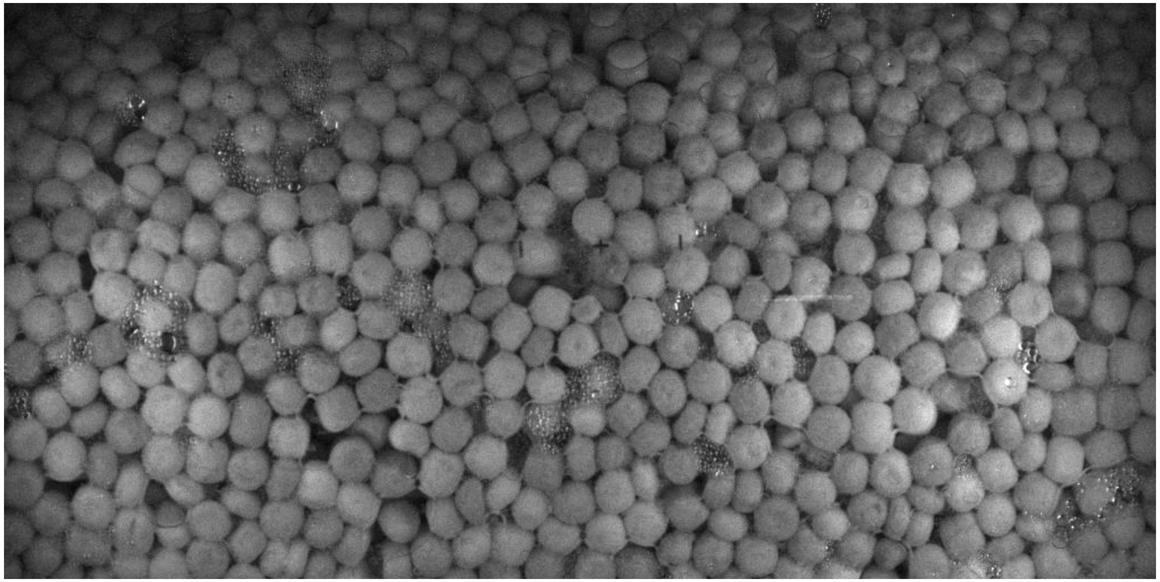


Large bubbles (darker spots) extending over multiple glass particle diameters

U_{GS} = 0.108 mm/s

U_{LS} = 1.03 mm/s

Large bubbles with Alumina packing
U_{GS} = 0.325 mm/s
U_{LS} = 0.412 mm/s



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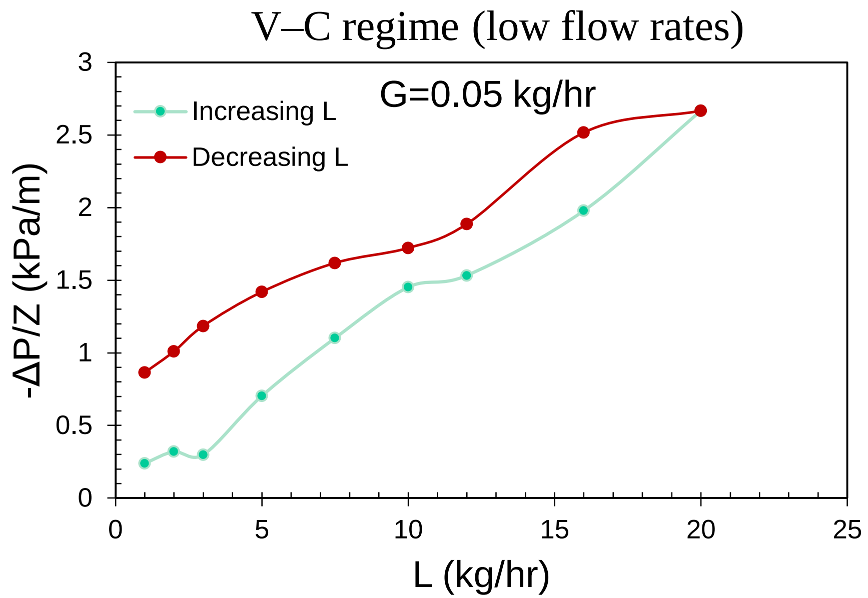
Pressure Gradient Contributors

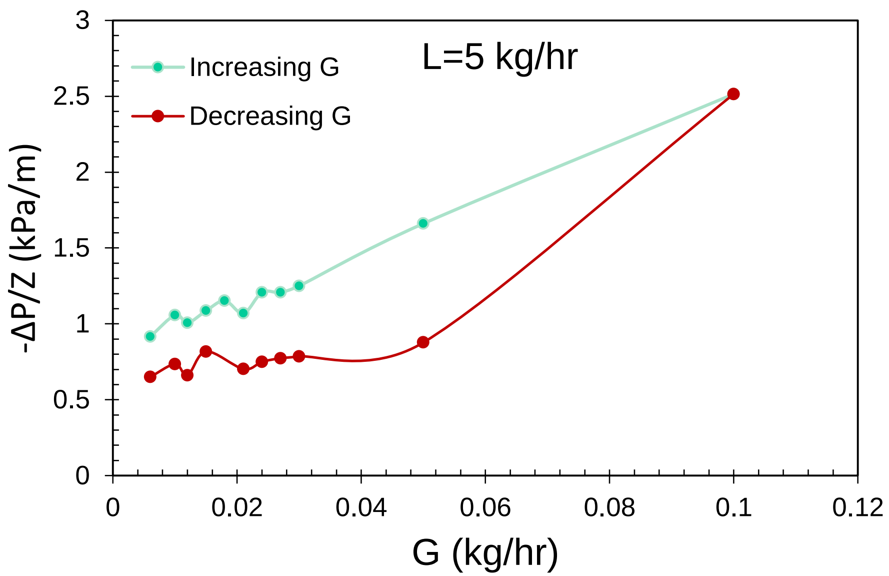
U_{LS} (mm/s)	U_{GS} (mm/s)	Experimental $-\Delta P/Z$ (Pa/m)	Calculated $-\Delta P/Z$ (Pa/m)	Capillary $-\Delta P/Z$ (%)	Viscous $-\Delta P/Z$ (%)	Inertial $-\Delta P/Z$ (%)	No-Slip Gas Fraction (%)
2.75	0.11	3219	3059	69.9	27.0	3.1	3.8
2.75	3.25	4745	5142	82.1	16.1	1.8	54.1
2.75	10.82	5765	6292	85.4	13.1	1.5	79.7
2.75	108.19	9916	9433	90.2	8.8	1.0	97.5
5.50	0.11	6228	6306	67.8	26.2	5.9	1.9
5.50	3.25	13585	10472	80.6	15.8	3.6	37.1
5.50	10.82	15767	12771	84.1	13.0	2.9	66.3
5.50	108.19	22101	19053	89.3	8.7	2.0	95.2
9.62	0.11	15563	11527	64.9	25.1	10.0	1.1
9.62	3.25	23254	18818	78.5	15.4	6.1	25.2
9.62	10.82	27149	22841	82.3	12.7	5.0	52.9
9.62	108.19	36478	33835	88.0	8.6	3.4	91.8
13.74	0.11	23454	17170	62.3	24.1	13.7	0.8
13.74	3.25	30777	27587	76.5	15.0	8.5	19.1
13.74	10.82	36438	33333	80.6	12.4	7.0	70.3
13.74	108.19	53287	49039	86.8	8.4	4.8	88.7
17.18	0.11	25536	16691	60.2	23.3	16.5	0.6
17.18	3.25	37079	28233	74.9	14.7	10.4	15.9
17.18	10.82	44997	36151	79.2	12.2	8.6	38.6
17.18	108.19	69439	60594	85.8	8.3	5.9	86.3
20.61	0.11	32968	27514	58.3	22.5	19.2	0.5
20.61	3.25	44062	43138	73.4	14.4	12.2	13.6
20.61	10.82	51501	51758	77.8	12.0	10.2	34.4
20.61	108.19	93346	75317	84.8	8.2	7.0	84.0

Capillary force is the dominant contributor to the pressure gradient

Capillary contribution to ΔP increases with increasing gas flow rate and decreasing liquid flow rate

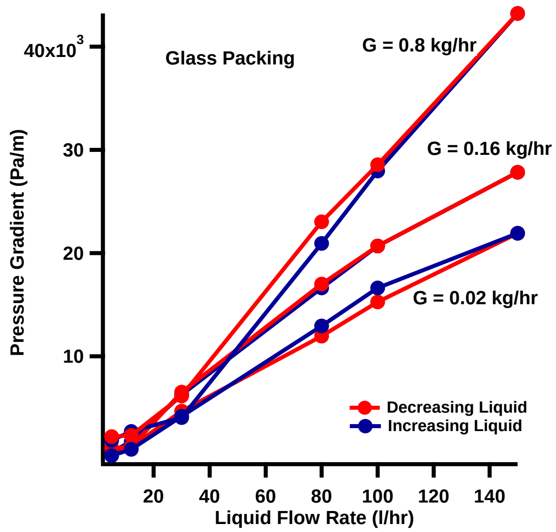
Hysteresis Effects





Increasing and then decreasing the liquid (gas) flow rate, at a fixed gas (liquid) flow leads to different values for the liquid holdup and pressure gradient

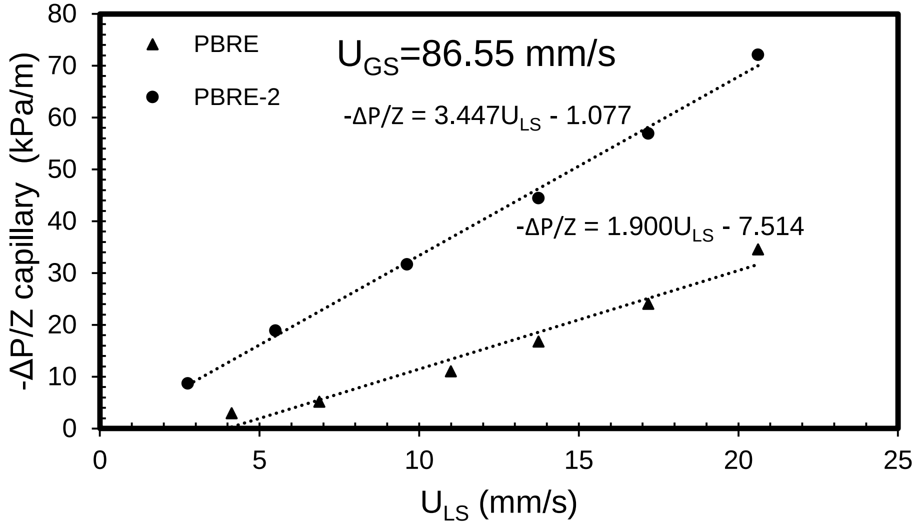
- ✓ Hysteresis effect exists within the V–C regime for both constant gas flow rate and constant liquid flow rate experiments.

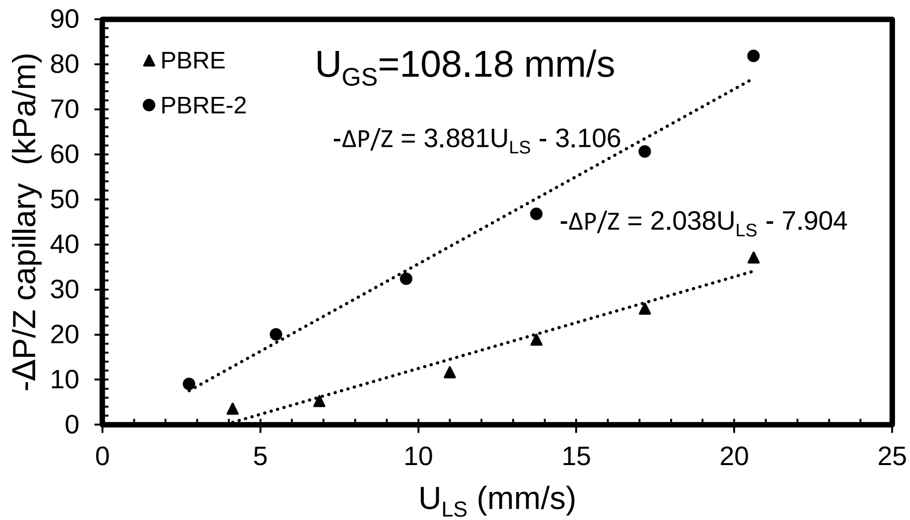


PBRE data
High flow rates

- ✓ The relative hysteresis magnitude was found to be negligible outside of the V–C regime for first series of PBRE experiments.

Effect of Particle Size





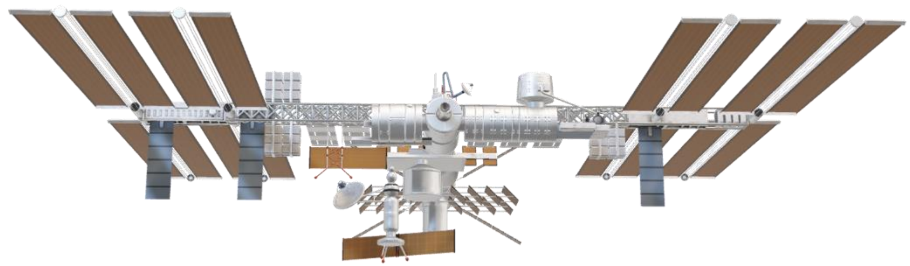
- ✓ The capillary pressure gradient is 1.5 to 2 times higher for the PBRE-2 2mm particles than the PBRE 3mm particles

$$(-\Delta P/Z)_{2mm} \Big/ (-\Delta P/Z)_{3mm} \approx \left(d_{p,3mm} \Big/ d_{p,2mm} \right)^{0.8\,to\,1.5} \approx 1.4 - 1.8$$

Packed Bed Reactor Experiment

Conclusions

- For gas and liquid flow rates of interest in most microgravity applications, there are four major flow patterns: dispersed bubble, pulse, elongated/large bubble, and gas continuous regimes.
- We developed an accurate flow pattern map for the N2-water system based on the change in slope of the pressure gradient with either gas or liquid flow rate.
- Dependence of the pressure gradient on gas and liquid flow rates is different in each flow regime. Hence, a separate correlation is presented here for the first time to make accurate predictions of the pressure drop in each flow regime.
- Capillary contribution to the pressure gradient is the dominant over all gas and liquid flow rates studied compared to inertial and viscous contributions.
- The capillary contribution is found to vary inversely with the particle diameter but its dependence on gas and liquid flow rates is different in different flow regimes.
- Hysteresis effects are observed at low gas and liquid flow rates but become negligible at higher flow rates.



Thank You!